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THE ORIGIN OF VEINS OF THE ASBESTIFORM MINERALS

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In its strict application the name asbestos is limited to the fibrous varieties of the monoclinic amphiboles. The term is commonly applied, however, to those minerals having a highly developed fibrous (asbestiform) structure. When such minerals occur in veins the fibers are parallel, and run transverse to the strike of the veins. Hence they have been called cross-fiber veins.

Microscopic examination shows that bundles consisting of thousands of fibers of chrysotile or amphibole asbestos behave as crystal units, an entire bundle exhibiting the same optical properties as any one of the component fibers. All asbestiform minerals have prismatic cleavage, and this suggests that the fibrous structure may be due to an abnormal development of the cleavage, or at least that the separation of the fibers takes place largely along cleavage planes. The highly fibrous structure of the asbestiform minerals is not, however, a crystallization phenomenon in the sense that it is due solely to the inherent physical properties of the crystal molecule, for all minerals having asbestiform varieties occur in non-fibrous as well as fibrous forms.

A comparative study of the occurrence of all commonly fibrous minerals indicates that the peculiar structure of asbestiform minerals is due to the accentuation of a normal prismatic habit and cleavage by physical conditions which have limited crystal growth to a direction parallel to the principal axis. *Many minerals possessing perfect prismatic cleavage do not have fibrous varieties*, but they are always minerals that crystallize from fusion or solution under conditions permitting of growth in more than a single direction. All asbestiform minerals are second-

ary and for the most part they are limited to metamorphic rocks. The primary minerals of igneous rocks are never fibrous. *Many minerals without prismatic cleavage have fibrous varieties.* They differ from asbestos in having fibers that are usually coarser, more brittle and not so easily separable. With fibers of equal size the flexibility and tensile strength are probably determined chiefly by chemical composition. When minerals do not have a columnar or prismatic habit, the fibrous structure is obviously due to mechanical conditions which have prevented growth except in one direction.

The shape of a growing crystal is controlled by one or more of three independent factors, namely: (1) the tendency to assume a regular polyhedral form because of the forces of surface tension and molecular orientation; (2) the relative and absolute magnitude of the external forces resisting growth in different directions; and (3) the accessibility of the material from which the crystal is built. As a result of the first factor some substances normally crystallize in slender acicular or hair-like forms, but an asbestiform structure is never produced without the assistance of one of the other two factors. Crystal growth under unequal pressure undoubtedly explains the development of fibrous structure in some instances. The solubility of most substances increases with the pressure and therefore crystal growth may be limited to the direction of least pressure. This hypothesis is not applicable, however, to fibers that develop normal to the walls of a vein. Moreover the veins frequently intersect and run in all directions through a given rock mass. Such occurrences of abnormal fibrous structure must therefore be attributed largely to the circumstance that the material for growth was accessible only in one direction.

The efficacy of this method of producing fibrous structure in crystals has been proved experimentally.¹ Cups of porous porcelain were partly immersed in concentrated solutions of copper sulphate, alum, and other salts, thus permitting the solutions to be drawn by capillary attraction into the upper and exposed walls of the cups. When the solutions occupying the small pores were supersaturated by evaporation or cooling so that crystallization began, fibrous crystals grew slowly outward from the surfaces of the cups.

Crystals also developed at favorable places within the walls of the cups, which were ruptured by the pressure as growth continued. The fractures thus formed were gradually extended and widened by the growth of fibrous veins, closely resembling in structure the cross-fiber veins found in rocks. The crystals have a fibrous structure because additions of new material were made only at their base. Using alum

solutions it was found possible to change the color of the material by adding chrome alum, and so prove experimentally that the fibers grew only at their base.

The development of the fibrous structure is probably aided by small adjustments or slips along the surfaces of the fiber prisms and cleavages when the latter are present.

Fibers of copper sulphate and alum are brittle and therefore difficultly separable, but some were obtained that had a length of several millimeters and a thickness of less than 0.001 mm. Such fibers are slightly flexible and somewhat elastic. Slender acicular forms are never found in crystals of copper sulphate or alum that have grown normally in free contact with solutions, because this form is not the most stable. The total surface energy of one of the acicular crystals is great as compared with the mass, and therefore they are dissolved by solutions that are supersaturated with respect to more stable forms.

Many theories² have been advanced in explanation of the origin of cross-fiber veins, particularly those of chrysotile. Most of these theories presuppose the existence of open fissures in which the vein minerals were deposited. It is conceivable that some cross-fiber veins may have been formed in pre-existing fissures, but in most cases this is mechanically impossible.

Dresser³ has pointed out the absurdity of this theory as applied to the chrysotile deposits of southern Quebec, Canada, where the veins run in all directions from vertical to horizontal, occasionally reaching a length of 100 feet, and in places occupy over 10% of the entire rock. According to Pratt⁴ and Diller⁵ the chrysotile veins in the Grand Canyon, Arizona, over 4000 feet below the rim, extend horizontally parallel to the bedding of the enclosing rocks for distances of 150 feet or more.

In many instances there is evidence that the formation of chrysotile veins and the alteration of the enclosing rock to form massive serpentine were contemporaneous processes; but the alteration of a rock to serpentine is usually accompanied by an increase in volume sufficient to close all appreciable openings. The lenticular shape of many veins is an argument against the theory of deposition in open fissures of mechanical origin.

It has been suggested that chrysotile veins may have been formed by some process of replacement, but no one has explained why serpentine should replace serpentine of the same chemical composition. Moreover, chrysotile veins never contain pseudomorphs or show any trace of an inherited structure. Replacement veins are characterized by great irregularity in width and lack of definite boundaries, while chrys-

otile veins are sometimes remarkably uniform in width, and always have well defined walls that are easily separable from the veins.

The last objection applies likewise to the hypothesis that chrysotile veins represent portions of the serpentine that have crystallized *in situ*. Recrystallization is a common phenomenon in rocks, but it is never confined to a narrow vein-like zone with sharply defined walls. If chrysotile can be formed by such a process, why is the ratio of chrysotile to massive serpentine limited? Why is the entire mass of serpentine never recrystallized to form chrysotile?

Not one of the theories previously cited satisfactorily explains the presence of one or several partings in some veins and their absence in others. They do not explain the angular inclusions of massive serpentine that frequently mark the partings in chrysotile veins and are also found irregularly distributed through them. They do not explain why the fibers are normal to the vein walls in some instances and oblique in others. They do not explain the presence of sharp bends in the fibers, nor veins of cross fiber that grade into slip fiber. In view of all these facts it must be concluded that previous theories are inadequate to explain the origin of fibrous veins.

As noted above, cross-fiber veins with structural features similar to those found in rocks have been produced in the laboratory where their formation and growth could be observed. The evidence thus obtained supplements that furnished by veins of fibrous minerals, and makes inevitable the conclusion that cross-fiber veins are formed through a process of lateral secretion the growing veins making room for themselves by pushing apart the enclosing walls.

The force that enables the growing veins to push apart their walls is not due to the tendency of a crystalline substance to assume a regular polyhedral form, for the columnar or fibrous structure of most minerals occurring in cross-fiber veins is not a crystallization property, but is caused by the conditions of growth.⁶ Under similar conditions the fibrous structure will develop in substances that crystallize in any of the systems of crystallization. In most cases it is not the normal habit, and therefore is unstable. The writer believes that the force is due chiefly to the expansion in volume which accompanies the separation of most solids from solution, for, as yet, he has obtained no pressure effects during the crystallization of substances that separate from solution with decrease in volume. When a substance separates from solution with increase in volume, the pressure developed depends on the magnitude of the forces resisting expansion, and may be much greater than the force required to crush the substance. It is improbable that pressure alone

can expel solutions occupying subcapillary pores in rocks; and in serpentine and other rocks found enclosing cross-fiber veins the openings are almost entirely subcapillary in size. In such cases the transfer of material to the growing vein is probably due to diffusion rather than to circulation.

A central parting is formed whenever fibers start to grow from both walls of a fracture, and apparently this always happens when veins develop along pre-existing fractures unless growth is limited to one side only. In laboratory experiments, growth is frequently limited to one side by the development of the fracture in such a direction as to cut the other side off from solutions furnishing material for growth. When the formation of the fracture and the beginning of vein growth are contemporaneous, the parting is absent because of simultaneous growth at both ends of the fibers—a fact proved in the laboratory by changing the color of the solutions so as to produce symmetrically banded veins. Partings may also result from a pause in the process of growth or from a slight displacement of the walls. The irregularity of some partings is due to the more rapid growth of groups of fibers most favorably situated to receive additions of new material.

The inclusions of wall rock found along central partings represent fragments formed when rupture occurred, and their position is due to the growth of the vein on both sides as new material was added through the walls. Occasionally vein matter begins to crystallize along an incipient fracture or line of weakness close to the vein, and in this way a fragment is gradually separated from the wall and included in the growing vein.

The fibers are always parallel to one another and extend in the direction in which the walls moved as they were pushed apart by vein growth. In most veins the fibers are normal to the walls because the latter have been forced directly apart, but when the walls have had also a lateral displacement because of the simultaneous growth of adjacent non-parallel veins or other causes, the fibers grow in the direction of the resultant motion. If the course of the vein is not straight, the fibers may be normal to the walls at one place and oblique at another. As long as the relative motion of the walls of a growing vein is in a straight line, the fibers are straight; any change in the direction of motion is immediately recorded by the slowly lengthening fibers. If the change in the direction of relative motion is gradual and continuous the fibers are curved; if abrupt, it results in the development of sharp bends. Sometimes the fibers of a chrysotile vein record several changes in the relative movement of the walls, and this gives a banded

appearance due to the unequal reflection of light where the fibers run in different directions.

The structural phenomena discussed in the preceding paragraphs all furnish evidence tending to confirm the writer's theory of the origin of cross-fiber veins, and they are difficult or impossible of explanation under any other hypothesis of vein formation hitherto advanced.

Conclusions. Cross-fiber veins are formed through a process of lateral secretion, the growing veins making room for themselves by pushing apart the enclosing walls. The fibrous structure is to be attributed largely to the mechanical limitation of crystal growth through the addition of new material in only one direction. In the case of the asbestiform minerals the fibrous structure is accentuated by a normal prismatic habit and cleavage.

¹ The experiments herein referred to are described in my more extended paper on "The Genesis of Asbestos and Asbestiform Minerals" which will appear in an early number of *Bull. Amer. Inst. Min. Eng.*

² For a review of these theories, see Fritz Cirkel, Chrysotile asbestos, its occurrence, exploitation, milling and uses, Ed. 2, *Canada Dept. of Mines, Mines Branch, Report No. 69* (1910); O. B. Hopkins, A report on the asbestos, talc and soapstone deposits of Georgia, *Geol. Survey Ga., Bull.* No. 29 (1914); and J. A. Dresser, Preliminary report on the serpentine and associated rocks of Southern Quebec, *Canada Dept. Mines Geol. Survey Mem.* No. 22 (1913),

³ Dresser, J. A., *Ibid.*, p. 65.

⁴ Pratt, J. H., Asbestos, *U. S. Geol. Survey Mineral Resources*, 1904, pp. 1137-1140 (1905).

⁵ Diller, J. S., Asbestos, *U. S. Geol. Survey Mineral Resources*, 1907, pt. II, pp. 720-721 (1908).

⁶ Taber, Stephen, The growth of crystals under external pressure, *Amer. J. Sci.*, ser. 4, 41, 532-556 (1916).

A NEW TEST OF THE SUBSIDENCE THEORY OF CORAL REEFS

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According to Charles Darwin's much-discussed theory, a barrier reef represents the upgrowth of a coral reef which originally fringed a sinking (generally volcanic) island; and an atoll reef represents a further upgrowth, completed in typical form after the central island has sunk below sea-level. Between the upgrowing reef and the subsiding, central island is a concavity or 'moat.' Through the accumulation of detritus and shells and skeletons of organisms inside the reef, the moat is slowly filled. Above the detrital covering of the moat surface is the water of the 'lagoon.' The subsidence is supposed to have progressed